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Analysis of Polygonal Distance Protection Relay of Transmission Line Affected by SMES Device

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Abstract

Because of unique advantages in rapid response and independent control of active and reactive power, Superconducting Magnetic Energy Storage (SMES) device will be widely used in the power system. The SMES exchanges power with power grid in the charging and discharging process, so it may affect the performance of protection relay of transmission line, which will lead to mal-operation. Based on SMES model, the tripping characteristic of polygonal distance relay for single-machine-infinite-bus system (SMIB) with SMES is studied in this paper, and PSCAD/EMTC simulations are carried out to investigate the performance of polygonal distance relay with SMES. The simulation results show the measured impedance of polygonal distance relay is changed by SMES, and polygonal distance relay will make mal-operation when faults occur in the boundary of protection zone. Also an improving distance relay is proposed to solve the problem.

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Keywords: Superconducting Magnetic Energy Storage; Distance relay; PSCAD simulation; Tripping Characteristic

1. Introduction

Combining efficient energy storage in lossless superconducting coil and rapid electronic energy converter of power electronic device, Superconducting Magnetic Energy Storage (SMES) is extensively applied to power system with the ability of power regulation and energy conversion[1-3]. The applications of SMES to power system include damping system oscillations, improving voltage stability, spinning reserve, compensation of fluctuating loads, load leveling, protection of critical loads, backup power supply, improving power system symmetry, and so on[4,5].

The protection relay is an electrical apparatus which is designed to calculate operating conditions on an electrical grid and trip circuit breakers when a fault is detected. Due to interaction of SMES device and power transmission system, the voltage and current in power grid will change accordingly, which may affect the operation characteristic of protection relay[6-10]. As the widely used relay in high voltage grid protection, distance protection relay may be affected by the introduction of SMES, so the mal-operation of distance protection relay will became a potential

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threat. Therefore it's of vital importance to analyze the impact of SMES on distance protection relay.

Based on SMES model and distance protection relay model, the influence of SMES on tripping characteristic of polygonal distance protection relay is discussed in this paper. To investigate the measured impedance of polygonal distance protection relay affected by SMES in different fault types and positions, a single-machine-infinite-bus system is built under PSCAD simulation environment. Also, an improving method is proposed to prevent the mal-operation of polygonal distance protection relay.

2. System model

A single-machine-infinite-bus system is shown in Fig1.(a). SMES with current source converter is connected to the transmission line through a transformer to reduce the operating voltage, and it consists of several sub-systems[1] such as superconducting coil, cryogenic container, refrigerating system, power conversion system, quench protection system and monitoring system, as shown in Fig1.(b).

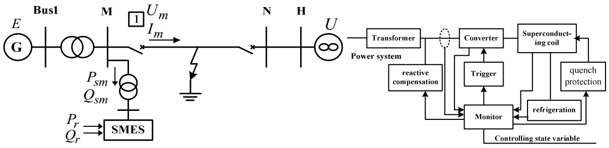


Fig.1(a) SMIB system with SMES (b)SMES model

The polygonal distance relay is configured at the beginning of the transmission line. And the criterion of measured impedance in polygonal distance relay is described as below[11,12]:

$$-90^\circ-\alpha_1\le\arg\frac{Z_m-R_{set}}{-R_{set}}\le 90^\circ-\alpha_1 \quad -90^\circ-\alpha_2\le\arg\frac{Z_m-\mathrm{j}X_{set}}{-jX_{set}}\le 90^\circ-\alpha_2 \quad (1)$$

$$Z_{m(phase)}=\frac{U_\phi}{I_\phi+k\cdot 3I_0} \qquad Z_{m(line)}=\frac{U_{\phi\phi}}{I_{\phi\phi}}$$

Where R_{set} and X_{set} are setting resistance and reactance, α_1 and α_2 are defined as 15° in general. U_ϕ and I_ϕ are single phase voltage and current, $U_{\phi\phi}$ and $I_{\phi\phi}$ are phase-to-phase voltage and current. I_0 is zero-sequence current , k is zero-sequence current compensating coefficient.

When the SMES is installed in the bus, we can get SMIB's equivalent circuit which is shown in Fig.2. The SMES regulates power by inserting current to the power system, so the SMES can be represented as a current source I_{sm}[3]. E_M , Z_M and I_f are equivalent electric potential, equivalent impedance and short-circuit current respectively.

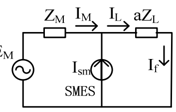


Fig.2 Equivalent circuit of SMES at the bus

In Equation(2), Z_m is the measured impedance and a is the ratio of line impedance at fault position to load impedance. I_m is the measured current. Z_{L} is the load impedance seen from the power side.

$$U_m=aZ_LI_L \qquad I_m=I_M \qquad (2)$$

$$I_L=I_{sm}+I_M \quad Z_m=\frac{U_m}{I_m}=aZ_L+\frac{I_{sm}}{I_M}aZ_L$$

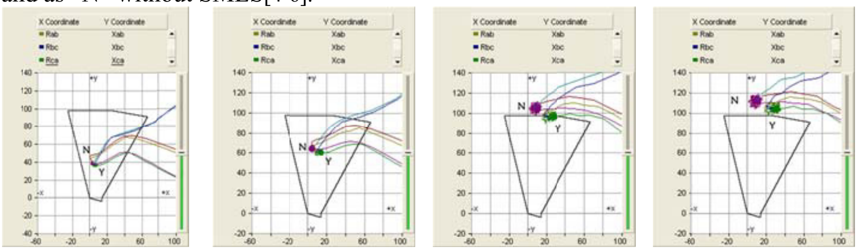
The measured impedance is aZ_L without SMES when three-fault-grounded fault happens. But when SMES is installed in the circuit, the measured impedance will be $aZ_L+\frac{I_{sm}}{I_M}aZ_L$, which is affected by the fault location a and I_{sm}. So the characteristic of distance relay may change correspondingly.

3. Simulation study

a. Simulation analyzation

As the simulation model shown in Fig.1, transmission line parameters are as follows: the length of transmission line from M to N $L_{MN} = 30km$, the length of transmission line from N to H $L_{NH} = 4km$, $r_1 = 0.013\Omega / km$, $x_1 = 0.5\Omega / km$. Superconducting coil parameters include $L_d = 7.8H$ [1-2], magnetizing current $I_{dc} = 4.0kA$, magnetizing power $P_h = 25MW$. Zone1 impedance setting of the polygonal distance relay is $Z^{\mathrm{I}}_{set} = (12.7 + j105.86)\Omega$, which can protect 80% of total line length. The simulation time is 8s, and a three-phase-ground fault at transmission line MN will occur at 5s and last 0.2s. (All data is obtained from multiple simulations.)

The simulation is repeated with different fault positions, including 50%, 81% and 85% of the line length. Simulation results of measured impedance with and without SMES are shown in Fig.3. Curves with SMES are marked as “Y” and as “N” without SMES[4-6].



(a) Fault at 30% of line (b) Fault at 50% of line (c) Fault at 81% of line (d) Fault at 85% of line

Fig.3 Measured impedance and tripping characteristic, SMES in bus (Units of both axes are Ω)

Fig.3 shows that measured impedance is different because of SMES, and the error of measured impedance increases with increasing a. Fig.3 (a) and (b) show that measured impedance is within the operating zone when fault occurs in 30% and 50% of line length, and that means the distance relay trips correctly. Fig.3 (c) shows that measured impedance enters the operating zone with SMES when the fault point is at 81% of line length which is out of protection zone; it means the distance relay will make mal-operation. The measured impedance stays outside of the operating zone whether with SMES or no SMES in Fig.3 (d), and the relay will not trip. When SMES is installed at the middle of the transmission line, we can get similar results.

Simulation results with different fault positions, fault types and SMES locations are shown in Table 1, in which “A-G” represents single-phase-ground fault, “BC-G” represents two-phase-ground fault and “ABC-G” represents three-phase-ground fault. “O” means trip of distance relay while “X” means mal-operation of distance relay.

Table.1 Simulation results of different fault positions, fault types and SMES locations

SMES location	In the bus			In the middle of transmission line		
Fault position	50%	81%	85%	50%	81%	85%
A-G	O	X	O	O	X	O
BC-G	O	X	O	O	X	O
ABC-G	O	X	O	O	X	O

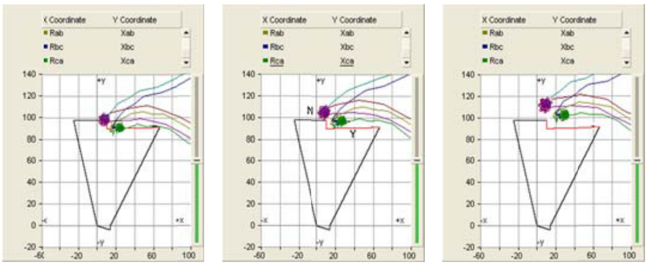
Fig.3 and Table 1 show that with SMES the distance relay works correctly in most situations only except fault occurring nearby the boundary of protecting zone, so SMES is disadvantageous to polygonal distance relay. And SMES in bus has greater effects on distance relay than SMES located in middle of the line.

b. An improved distant relay

Mal-operation only happens when the fault location is nearby the boundaries of the operation zone, so the measured impedance is just slightly impacted by SMES. To improve the operation characteristic of polygonal distance relay, a new tripping boundary is proposed to prevent mal-operation. Because the error of measured impedance increases with a increasing, the most serious error which will cause mal-operation occurs when fault point is just at the boundary of protecting zone. So the new operating zone can be recalculated to avoid the most serious fault, which occurs at 80% of line length. Fig.4 shows the new protection zone of measured impedance, and the results are summarized in Table 2 to show the operation results of polygonal distance relay. Fig.4 and Table 2 show that the improved distance relay will not make mal-operation when faults occur in the boundary of protecting zone with SMES. Also, the improved distance relay can trip correctly when faults occur within the protection zone. The operating zone of improved distance relay is denoted as follow, which is shown in Fig.4.

$$\begin{cases} X_m < X_{set} - Imag(\dfrac{I_{sm_{\max}}}{I_{M_{\max}}} a_{set.1} Z_L) \\ R_m < R_{set} - Real(\dfrac{I_{sm_{\max}}}{I_{M_{\max}}} a_{set.1} Z_L) \\ -90^{\circ} - \alpha_1 \le \arg \dfrac{Z_m - R_{set}}{-R_{set}} \le 90^{\circ} - \alpha_1 \\ -90^{\circ} - \alpha_2 \le \arg \dfrac{Z_m - \mathrm{j}X_{set}}{-jX_{set}} \le 90^{\circ} - \alpha_2 \end{cases} \tag{3}$$

Where $I_{sm_{\max}}$, $I_{M_{\max}}$ and $a_{set.1}$ are the values when the three-phase fault occurs at boundary of protecting zone respectively.



(a) Fault at 79% of line *(b) Fault at 81% of line* *(c) Fault at 85% of line*

Fig.4.Measured impedance and new tripping characteristic (Unit of both axes is Ω)

Table.2 Simulation results of different fault positions, fault types and SMES locations

SMES location	In the bus			In the middle of transmission line		
Fault position	50%	81%	85%	50%	81%	85%
A-G	O	O	O	O	O	O
BC-G	O	O	O	O	O	O
ABC-G	O	O	O	O	O	O

4. **Conclusions**

SMES device is characterized with unique advantages as four-quadrant power modulation and it can improve the safety and stability of power system. However its charging and discharging process may have impact on the transmission line protection. The effect of SMES on polygonal distance relay is analyzed in this paper in detail, and simulations are carried out to investigate the operation characteristic of polygonal distance relay by PSCAD. The simulation results show that the measured impedance changes with SMES, and polygonal distance relay makes mal-operation when faults occur in the boundaries of protection zone. An improved distance relay is proposed to solve the problem, and its availability is verified by corresponding simulation results.

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